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INFLUENCE OF FUEL INJECTOR HOLES DIAMETER ON PARAMETERS OF COMBUSTION PROCESS IN THE CYLINDER OF THE MARINE 4-STROKE DIESEL ENGINE

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Abstract

The paper presents an analysis of the influence of the fuel injector nozzle holes diameter on parameters of the brake-up, evaporation and combustion process in the cylinder of the marine 4-stroke Diesel engine. Presented analysis was prepared in the basis on computational fluid dynamic model. Initial and boundary conditions of the model as well as data used to model validation were collected during the laboratory study. Calculations were conducted for nominal fuel holes diameter equals 0.375mm and diameters increased and decreased by 50μm and 100μm respectively. According to presented results the increase of the diameter of fuel nozzle holes causes the increase of fuel Sauter's mean diameter in the initial stage of the injection process and the decrease of fuel process evaporation. The result of this phenomenon is the slowdown of the initial stage of the combustion process and the decrease of both pressure and temperature of combustion.

Keywords: marine engine, multidimensional model, combustion model, fuel injection, holes diameter

1. Introduction

The increase of the requirements of environmental protection imposes on constructors of marine engines the necessity of constantly improve its design. The decrease of the fuel consumption of marine engines and simultaneously the decrease of combustion temperature, required for limit the nitric oxides emission, requires modifications in the organization of the combustion process. Mentioned modifications of the combustion process consist in provide fuel into the Diesel engine cylinder in appropriate time and suitable properties. Its amounts to determine the characteristics of the mass flow rate of fuel injection of the appropriate shape, dependent on the shape of the combustion chamber. In works [1] and [2] the influence of the fuel nozzle holes convergence on combustion process parameters is presented. Conical shape of fuel nozzle holes causes the increase of both the fuel penetration and flow speed. Authors of works [3], [4] and [5] present the influence of the fuel nozzle holes group location on fuel injection parameters. The nozzle holes configuration influences on the fuel penetration in the combustion chamber, the Sauter's mean diameter of the fuel spray and the auto-ignition delay. According to results presented in [6], [7] and [8], the shape of fuel nozzle holes edges is an important parameter influences on the fuel spray geometry. Narrow edges promote the cavitation phenomenon in nozzle holes and increase the vaporization process. The fuel viscosity and other parameters influence on the fuel evaporation, the auto-ignition and the combustion are presented in [9], [10] and [11]. It should be noted that the movement of mixture in the combustion chamber of the Diesel engine influences on the combustion parameters also [12], [13]. All presented works concerns the fuel injection process in small engines in relation to marine engines. Fuel injection in large marine engines usually is controlled by Bosch type fuel pumps and the diameter of fuel nozzles holes is significantly larger. Thus the main aim of presented work is the analysis of the influence of the fuel nozzle holes diameter on parameters of the combustion process in the marine engine. Mentioned analysis is prepared in the basis on the computational fluid dynamic model of the combustion process. Initial and boundary conditions are taken from direct measurements. It should be noted that the analysis is prepared for changed diameters of fuel nozzles holes without changing the rest parameters on fuel injection i.e. the fuel mass flow characteristic and initial conditions (the compression process).

2. The model description

The base of the combustion process model in the engine cylinder is a geometric grid, including the shapes of the cylinder with the air intake duct, the outlet duct and exhaust and inlet valves. The geometric grid was built in the basis on the technical documentation of the research object. As a research object the laboratory 4-stroke engine, type Sulzer Al25/30 was selected. The analysis and the selection of geometric grid parameters are presented in [6]. Parameters of the Al25/30 engine are presented in Tab.1.

Tab. 1. The laboratory engine parameters

Parameter	Value	Unit
Max. electric power	250	kW
Rotational speed	750	rpm
Cylinder number	3	–
Cylinder bore	250	mm
Stroke	300	mm
Compression ratio	12.7	–
Injector nozzle		
Holes number	9	–
Holes diameter	0.325	mm
Holes position diameter	7	mm
Holes position angle	150	deg.
Spray cone angle	6	deg.
Opening pressure	25	MPa

The fuel injection model is based on geometrical dimensions of the injector nozzle, which are presented in Tab.1 also. Measured injection timing equals to 18 degrees before top dead center of the piston position. The delay between pressure signal in the indicator valve and the combustion pressure is neglected. The initial value of the droplet diameter of the fuel injection is taken as the diameter of fuel nozzle holes. A further break-up of fuel droplets has been described by the Lagrange description [15] with TAB model application [16]. This model specifies the conditions for breaking-up of fuel droplets as a dimensionless factor that depends on the density of fuel and surrounded air, the viscosity of the fuel droplet, the relative velocity and the diameter of droplets. If the value of the mentioned factor is greater than 1, the droplet breaks up. Distribution of the mean droplet diameter, determined by the Sauter's method [15], is assumed as the Chi^2 distribution.

Simultaneously with the fuel atomization process the process of evaporation begins. This process results from the heating of fuel droplets. For modeling the heat flow from air to fuel droplets and the mass flow of fuel vapors from droplets to air the Dukowicz's model is adopted [17]. The spherical shape of fuel droplets (microgravity conditions) and a constant temperature and heat transfer conditions on the surface of the droplet is assumed.

Evaporated fuel is mixed with air in the engine cylinder. To modeling these phenomena the k-ε model [18] were used. The combustion process was described by the ECFM-3Z model [18]. It is a model developed for modeling the combustion in diesel engines and it belongs to the CFM (Coherent

Flame Model) class of models. This model assumes that the chemical reactions take place in the relatively thin layer of the flame. The flame progresses to the direction of fresh mixture of air and fuel. Mentioned flame layer is defined as homogeneous mixture of fuel and air and its shape and size is defined by diffusion phenomena. In the present model, the auto-ignition delay is determined by air temperature, the density of the mixture and the molar concentration of oxygen and fuel. Chemical kinetic calculations are prepared for assumed substitute fuel composition in the form of $C_{13}H_{23}$ hydrocarbon. The detailed description of the model is presented in [20].

3. The laboratory stand

Boundary and initial conditions, as well as data necessary for the validation of this model were collected during laboratory tests. During the laboratory research the engine operates at a constant speed equals 750rpm and constant load equals 250kW. The engine was fueled by diesel oil with known specifications. The research covered the registration of parameters of turbocharger, fuel system, lubrication, cooling and air exchange systems. All parameters are measure with a sampling time equal to 1 second and used for modeling the data was the arithmetic average of 3 observations. Closer description of laboratory research can be found in [21] and [22].

4. The validation model and obtained results

The validation of model results was carried out according to combustion pressure and nitric oxides and oxygen fractions in exhaust gas. During the presented research thermodynamic parameters of both exhaust gas and charge air have been not compared due to use mentioned parameters as initial and boundary conditions. According to results presented in [20] the maximum error between calculated and measured values of the combustion pressure equals 6.8% for 28% of the maximum engine load. The average value of the error for calculated results in comparison to measured values for all considered the engine loads equals 1.2% for nitric oxides fraction and 0.4% for the oxygen fraction in exhaust gas.

Positive validation of model results allows to the calculation for different diameters of fuel injector nozzle holes. Calculations were prepared for larger and smallest diameters of mentioned holes in relation to diameter presented in Tab.1. Values of chosen diameters are presented in Tab.2. The rest parameters of injection were not changed, especially the mass characteristic of fuel injection and initial and boundary conditions.

Tab. 2. Chosen diameters of fuel nozzle holes

Diameter [mm]	0.225	0.275	0.325	0.375	0.425
Diameter changes in relation to laboratory research [μm]	-100	-50	0	+50	+100

The decrease of the diameter of fuel nozzle holes helps the brake-up and the vaporization of fuel [23]. The influence of the diameter of nozzle holes on the Sauter's mean droplet diameter and the quantity of evaporated fuel are presented on the Fig.1.

According to presented results the increase of the nozzle holes diameter causes the increase of the Sauter's mean diameter of fuel droplets in the initial stage of the injection process. The effect of this phenomenon is slowdown of the fuel evaporation and the auto-ignition. In the case of maximum considered holes diameters the fuel auto-ignition was calculated after 5.1°CA after the start of the fuel injection. For the minimum holes diameter this delay equals 3.8°CA. According to presented on the Fig.1 results for the 0.225mm fuel nozzle holes diameter, the quantity of the evaporated fuel until auto-ignition equals 9.6%. For the 0.425mm holes diameter this fuel quantity equals only 3.2% of fuel dose. According to this situation the initial stage of the combustion process is faster.

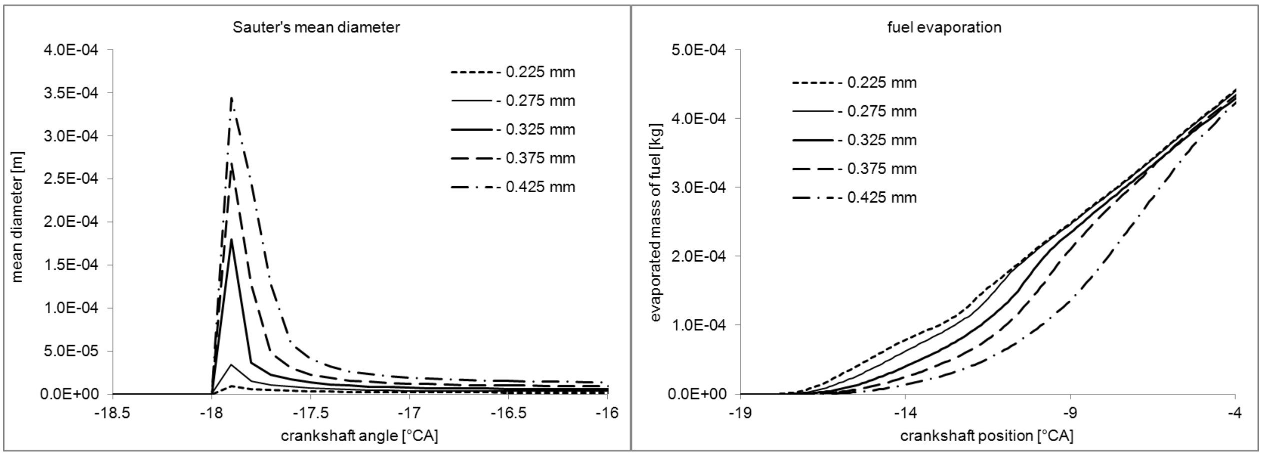

Fig.1. Sauter's mean diameter of the fuel droplet and fuel evaporation changes

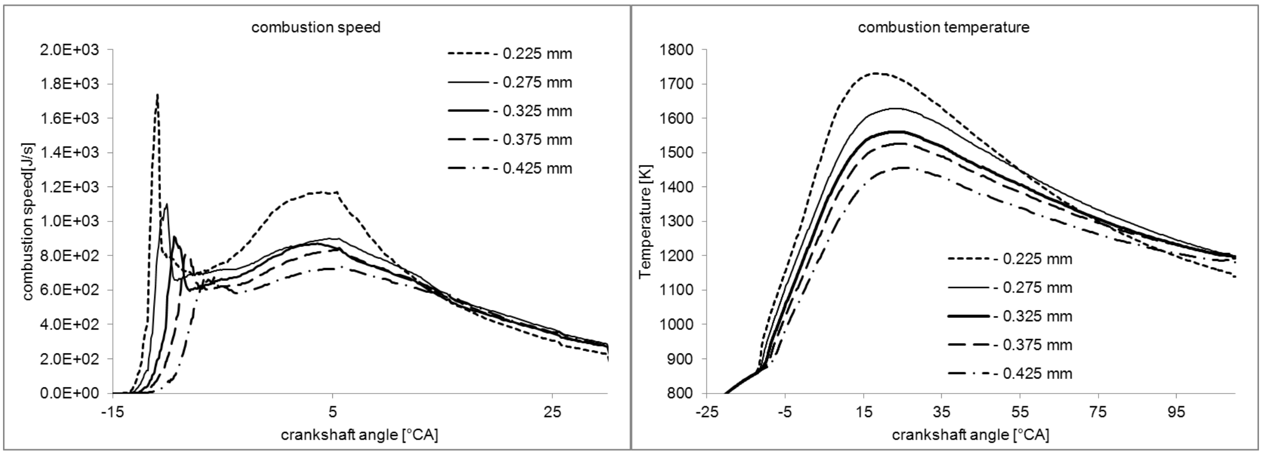

Fig.2. Calculation results for the combustion speed and combustion temperature

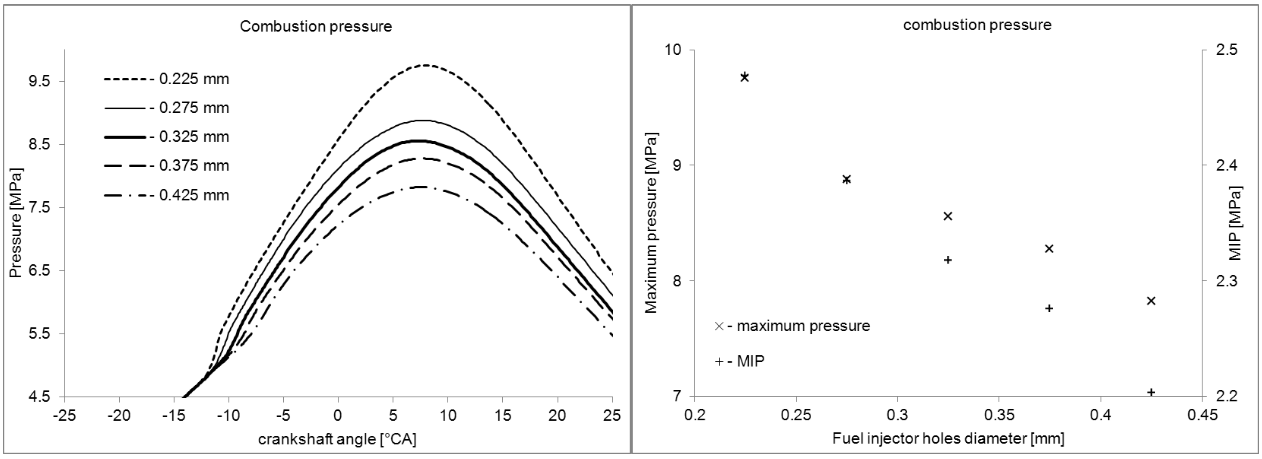

Fig.3. Calculated combustion pressure

Fig.2 presents the influence of the fuel nozzle holes diameter on the combustion speed and combustion temperature. The decrease of the nozzle holes diameter promotes shortening the penetration of not evaporated fuel but the quickness of the fuel propagation in the combustion chamber is higher. The explanation of presented phenomenon is the increase of pressure and the flow rate of fuel through nozzle holes. It should be noted that the decrease of fuel nozzle holes with the same number of holes causes the decrease of the cross section area of the fuel flow. The constant fuel mass flow characteristic causes the increased fuel injection pressure.

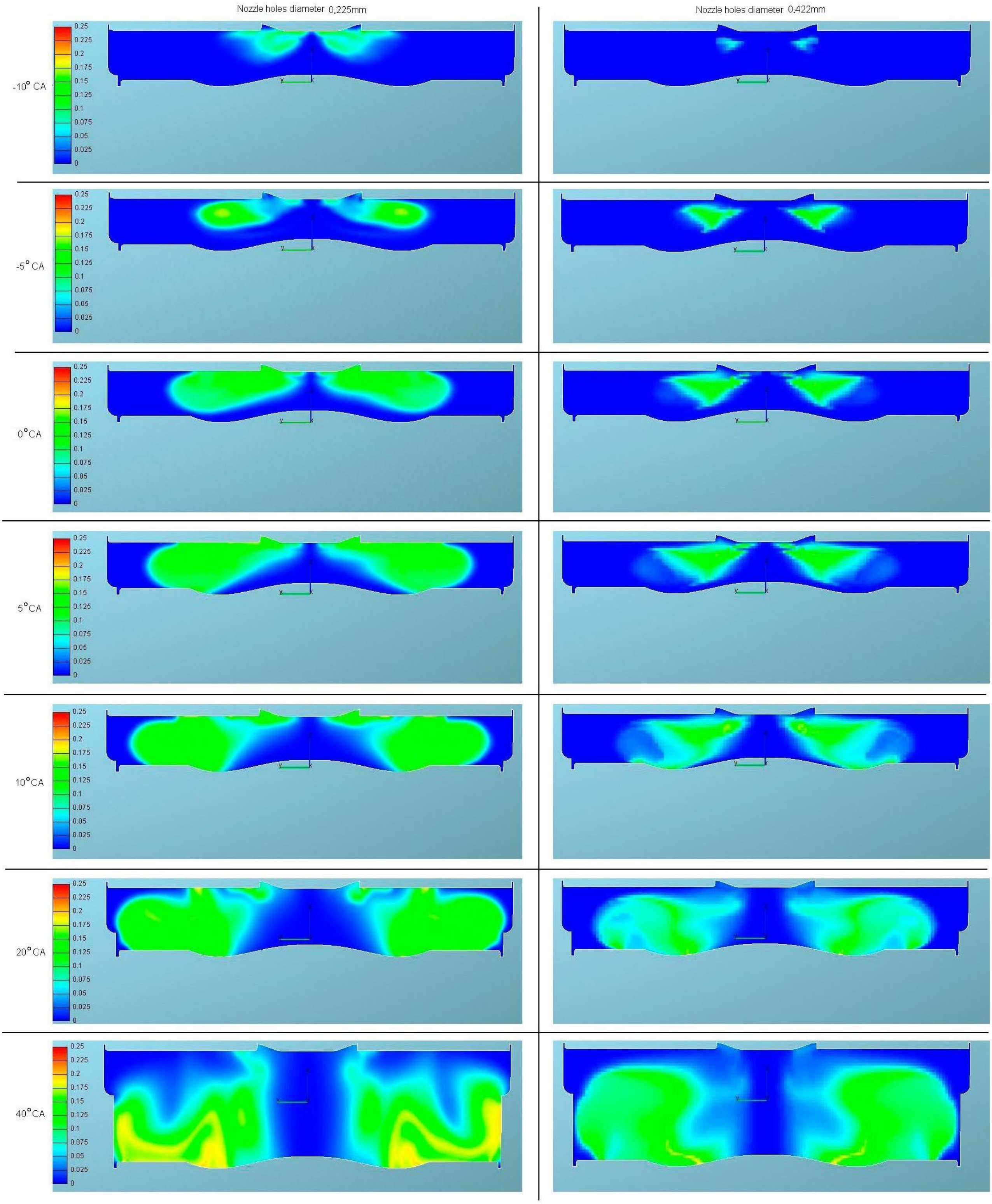

Fig.4. Carbon dioxide (CO_2) fractions in the engine cylinder

This phenomenon promotes the increase of the intensity of the fuel evaporation and the increase of the intensity of the fuel auto-ignition and the combustion. The difference between the chosen diameter of fuel nozzle holes causes the difference in the auto-ignition equals 1,3ºCA. Presented on the Fig.2 the increase of the combustion speed causes the increase of combustion temperature. According to results presented in [24] the increase of the fuel injection pressure causes the increase of the maximum combustion pressure. On the Fig.3 the influence of the nozzles fuel diameter on combustion pressure is presented. According to presented results the decrease of the fuel nozzle holes diameter causes not only the increase of combustion temperature but the increase of combustion pressure is observed also. Considered change of the fuel nozzle holes diameter causes 12% changes in the mean indicator pressure (MIP) also. Presented result is expected. Modification of the combustion process to extend the kinetic stage of the combustion is desirable in modern constructions of Diesel engines [25]. According to this it should be concluded that in presented construction of the combustion chamber of the engine the decrease of the fuel nozzle holes diameter causes the increase of the combustion efficiency.

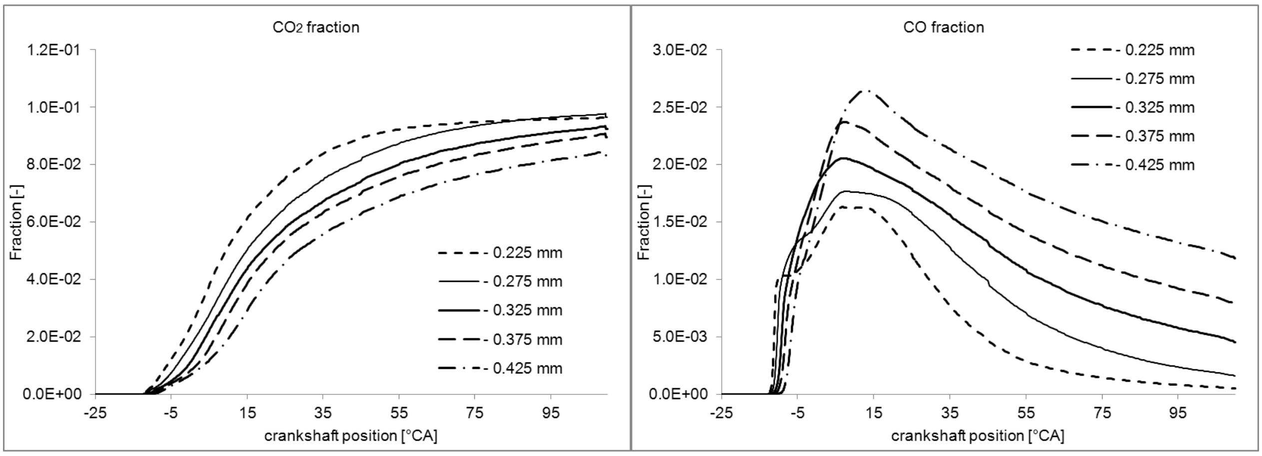

Fig.5. CO_2 and carbon monoxide (CO) fractions in the engine cylinder

Fig.4 shows the visualization of the CO_2 mass fraction in the combustion chamber of the engine. Mentioned fractions are presented for chosen angles of crankshaft position (CA) and chosen extreme values of fuel nozzle hole diameters. It should be noted that mass fraction of the CO_2 coresponds with combustion chamber areas where the combustion process comes to end. According to presented results, the fuel nozzle holes diameter equals 0.225 mm causes the increase speed of combustion. Near 20°CA the most quantity of the CO_2 is within combusted fuel but after the next 20°CA the CO_2 spreads to the entire volume of the cylinder. The increase of the diameter of fuel nozzle holes causes the extension of the combustion proces after the 40°CA. Mean values of the CO_2 and the CO for overal volume of the engine cylinder are presentrd on Fig.5. According to presented results the increase of the diameter of fuel nozzles holes causes the decrease of CO_2 fraction and the increase of CO fraction in the engine cylinder. Presented results confirms conclusion about the increase intensity of the combustion process with the decrease of the diameter of fuel nozzle holes.

5. Conclusions

The paper presents the calculation on the combustion process in the cylinder of the marine 4-stroke Diesel engine. Calculations were prepared by computational fluid dynamic methodology. Obtained model was validated according to combustion pressure and the nitric oxides and the oxygen mass fractions in the combustion chamber of the engine. The validation data and initial and boundary conditions were collected during the laboratory study. The main purpose of the work was analysis the influence of the diameter of fuel nozzle holes on parameters of the combustion process. Obtained results allow specifying following conclusions:

– The increase of the diameter of fuel nozzle holes causes the increase of Sauter's mean diameter of the fuel spray during the initial stage of the injection process. The result of this is slowdown of the fuel evaporation and the combustion process.

– The result of the slowdown of the evaporation process is the slowdown of the fuel auto-ignition. The difference between chosen diameters of fuel nozzle holes causes the difference in the auto-ignition equals 1.3°CA.

– In the case of the 0.225mm fuel nozzle holes diameter, the quantity of the evaporated fuel until the auto-ignition equals 9.6% of the fuel dose. For the 0.425mm holes diameter this fuel quantity equals only 3.2% of fuel dose. According to this result it should be concluded that the decrease of the diameter of fuel nozzle holes causes the increase of the speed of both the kinetic and the diffusion stage of the combustion.

– The decrease of the diameter of fuel nozzle holes causes the increase of both temperature and pressure of the combustion. It should be noted that the MIP increased also. It means that the decrease of the diameter of fuel nozzle holes causes the increase of the combustion efficiency.

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